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Contextualizing the EU's "Responsible Research and Innovation" Policy in Science Education: A Conceptual Comparison with the Nature of Science Concept and Practical Examples

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ABSTRACT

The European Union (EU) encourages science education to be oriented towards the concept of Responsible Research and Innovation (RRI), i.e. socially and ethically sensitive and inclusive processes of science and technology. Connecting RRI to prevailing concepts in science education, such as the Nature of Science (NoS), may facilitate the incorporation of RRI in curricula and classrooms. We carried out a conceptual comparison between the EU's RRI policy and a recent reconceptualization of NoS, known as the expanded Family Resemblance Approach. We discuss how the socio-institutional nature of science in that approach closely connects to the RRI and can provide a means for RRI teaching. To illustrate these opportunities, we present practical classroom approaches developed in the EU-funded project IRRESISTIBLE, and survey results on teachers' perspectives on RRI. The aim of this work is to understand better the potential implications of RRI to research and practice in science education.

Keywords: family resemblance approach, nature of science, responsible research and innovation, teachers' attitudes

INTRODUCTION

Responsible Research and Innovation (RRI) was introduced as a cross-cutting political aim in the 7th Framework Programme of the European Union (EU), and it continues to be a key concept in the current Horizon 2020 programme (Owen, Macnaghten, & Stilgoe, 2012). RRI entails a socially and ethically sensitive and inclusive process of science and technology (European Commission, 2012) which pushes academia and the industrial research and development sector to cultivate their practices and engage more deeply with the remainder of the society. The aim is to ensure that societal actors work together, mutually responsively, from the beginning to the end of research and innovation process, and that both the processes and outcomes of research and innovation are aligned with the values, needs and expectations of the European societies.

A number of calls and projects have been initiated to this end. So far, the process has made universities develop their curricula (see e.g. the HEIRRI project) to address RRI in higher education, and made industry and its stakeholders adjust their practices accordingly (see e.g. projects EnRRICH, BigPicnic, COMPASS, HEIRRI, JERRI, MARINA, NewHoRRIzon, ProGReSS, OpenUP, PRISMA, PROSO, Res-AGorA, RRI-ICT Forum, RRI-Practice, SATORI, SIS-RRI, SMART-map, STARBIOS 2). However, reaching the RRI goal of involving societal actors in research and innovation needs not only researcher training and new management systems in academia, but also a

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Contribution of this paper to the literature

- The study analyses the implications of the EU's "Responsible Research and Innovation" (RRI) policy to research and practice in science education.
- The study shows the connections of the RRI policy to the Nature of Science concept.
- The study illustrates the opportunities and challenges of incorporating RRI in science education by presenting practical classroom approaches and results on teachers' attitudes.

change of thinking by the rest of society. School (science) education is a key to that, in order to raise a generation which does not want to sit outside the processes of science and innovation. The recent recommendations of the expert group visioning the European agenda of 'Science Education for Responsible Citizenship' explicitly state that "Science teachers and educators also have a responsibility to embed concepts of Responsible Research and Innovation (RRI) directly into their teaching" (European Commission, 2015, p. 22). Considering the great influence of earlier EU policy documents – for example the push from the 'Science Education Now: A Renewed Pedagogy for the Future of Europe' report (European Commission, 2007) for the inquiry-based science education movement – it is likely that the concept of responsibility will be at the core of European science education in coming decades.

This long-term agenda has been implemented by the EU, by launching a number of RRI-related calls in science education in the H2020 programme and the earlier Framework Programme 7. Projects focusing on primary/secondary education include ENGAGE, IRRESISTIBLE, PARRISE, and RRI Tools. While the concept of RRI has not yet been embedded in national school education systems (Kearney, 2016), through these initiatives RRI is likely to have an influence in teacher professional development (de Vocht, Laherto & Parchmann, 2017) and school science across Europe. (For an overview of these projects and their approaches to RRI in science education, see Blonder, Zemler, & Rosenfeld, 2016). The number of such initiatives will grow, at least if the recommendations of science education experts (European Commission, 2015, p. 32) are followed.

The abovementioned projects have, however, faced challenges in contextualising RRI for science classrooms at primary and secondary levels (Blonder et al., 2016; de Vocht & Laherto, 2017). Identifying RRI related aspects that can be embedded in practices is more difficult in schools than in research. Researchers, for example, can engage more in public participation and 'citizen science' projects, and academia can strengthen its processes for addressing the ethical, social and equity concerns. Tools for these purposes have already been developed (see e.g. RRI Tools and toolkit.pe2020.eu). For schools and teachers, however, finding the common ground with RRI aims requires more elaboration. What knowledge and skills will the new generation need to be active citizens and professionals in the sense of RRI, and what kind of educational approaches support those objectives? Contextualising RRI in science education would be important since the impact of RRI in science education depends on how it resonates with and contributes to the current frameworks, approaches and activities of science education (de Vocht et al., 2017; de Vocht & Laherto, 2017).

RRI evidently contains ideas similar to several more established approaches in science education. Some of these connections have been studied already – for example, the PARRISE project took the Socio-Scientific Issues (SSI) framework (Sadler, Barab & Scott, 2007) to contextualise RRI in science education (Kárpáti & Király, 2016), and the RRI dimensions were also reflected against the SSI framework in the IRRESISTIBLE project (Blonder et al., 2016; Blonder, Rap, Zemler, & Rosenfeld, 2017). The ENGAGE, IRRESISTIBLE and PARRISE projects also embedded RRI in the inquiry-based science education (IBSE) approach, and the meaning of "responsibility" in inquiry-based learning has also been analysed in the Ark of Inquiry project (Bardone, Burget, Saage, & Taaler, 2007). However, RRI has not been elaborated with respect to the framework of Nature of Science (NoS) in science education (Erduran & Dagher, 2014; Lederman, 2007) – although there is an evident connection between these concepts.

In this paper we analyse the concept of RRI in relation to the framework of NoS in science education. The aim is to conceptualize RRI for science classrooms and to understand better the potential implications of RRI to research and practice in NoS teaching and learning. To illustrate and discuss the relationships, opportunities and challenges of incorporating RRI in science education, we discuss the results and experiences of the IRRESISTIBLE project: practical classroom approaches and teachers' attitudes.

NATURE OF SCIENCE (NoS) IN SCIENCE EDUCATION

Nature of Science (NoS) is a predominant concept in research on science education as well as in reforms of science curricula. NoS education is uniformly advocated, since understanding the scientific processes and the relationships between science and society is considered to be a crucially important element of scientific literacy for all (e.g. Allchin, 2011; Roberts, 2007; Rudoph, 2000; Wenning, 2006). Yet, both the content and the approaches of NoS teaching have remained under debate. The most influential attempt to consolidate the concept has been the 'consensus model' (Lederman, 2007) listing the general characteristics of science and scientific knowledge such as tentativeness, non-linearity, theory-ladedness, roles of observation, inference and theoretical entities, distinction between theories and laws, use of models, creativity, and social and cultural embeddedness (Lederman, 2007; McComas & Olson, 1998).

The consensus model has brought about a myriad of empirical research (Lederman & Lederman, 2014), pointing out shortcomings in students' and teachers' understanding of NoS and, typically, recommending a reflective and explicit teaching of the NoS features. The consensus model has also been increasingly criticized as incomplete and fragmented (e.g. Allchin, 2011). Elby and Hammer (2001) argued that generalizations such as "scientific knowledge is tentative" may be neither correct nor productive when they do not attend the context. Furthermore, while the consensus model chiefly concerns the cognitive and epistemic aspects of science and scientific knowledge, current trends in science education such as scientific literacy for all (Roberts, 2007; Roberts & Bybee, 2014), the socio-scientific issues framework (Sadler et al., 2007) and the responsibility aspects (European Commission, 2015) have emphasized the meanings of science as a social process and societal endeavour.

To address the critique and to articulate the complexity and social embeddedness of science better, the consensus view of NoS has recently been challenged by the Family Resemblance Approach (FRA) (Irzik & Nola, 2011, 2014). The FRA aims to provide a more elaborated, dynamic, holistic and systematic representation of science, not merely as epistemic inquiry but also as a social institution. The FRA implies that different sciences have a family resemblance, i.e. they include a sufficient number of similarities and partial overlaps. While the consensus view tends to address ideas about science quite separately, the FRA specifically aims to scrutinise the interrelatedness of those common characteristics.

The FRA considers science both as a cognitive-epistemic system and as a social institution (Irzik & Nola, 2014). The cognitive-epistemic system consists of four categories: Scientific Practices, Aims & Values of Science, Scientific Methods & Methodological Rules, and Scientific Knowledge. These should all be taught in authentic contexts so that students see how all the elements evolve and are unified. Science as a social institution consists of four categories: professional activities (publishing, reviewing, informing the public, etc.), scientific ethos (honesty, openness, critical attitude, universalism, respect for subjects and nature, etc.), social certification & dissemination (peer review; books & journals, etc.) and social values of science (autonomy, social utility, etc.) (Irzik & Nola, 2014).

In their expanded version of FRA for Nature of Science, Erduran and Dagher (2014) added three categories that they argued were missing from the original FRA: social organisation and interactions, political power structures, and financial systems (the outer ring in **Figure 1**). The Expanded FRA (Erduran & Dagher, 2014) aims to develop further Irzik's and Nola's FRA to NoS for science education both theoretically and practically.

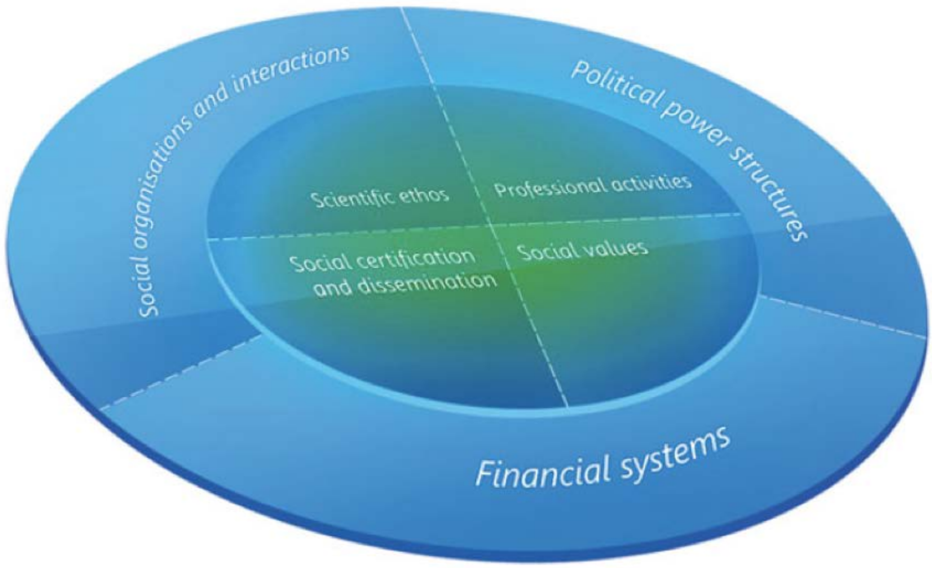

Figure 1. Science as a social-institutional system in the Expanded Family Resemblance Approach wheel (Erduran & Dagher, 2014; based on Irzik & Nola, 2014). Reprinted by permission from Springer Customer Service Centre GmbH: Springer Nature, *Reconceptualizing the Nature of Science for Science Education: Scientific Knowledge, Practices and Other Family Categories* by Erduran, S., & Dagher, Z. (2014)

The suggestions that FRA presents an alternative to the consensus view have led to criticism. For instance, it has been alleged that it is too advanced for high school students. Furthermore, Lederman and Lederman (2014) argued that although FRA is formatted as a matrix, it is still just another list of features of science just as the consensus view is. Irzik and Nola (2014) responded that this argument misunderstands how the FRA was intended to be used. In any case, the FRA has become a serious alternative to the consensus view. It has already gained kudos from empirical evidence, and been proven to be fruitful in teacher education (Erduran & Dagher, 2014).

The concept of Responsible Research and Innovation, further discussed in the next section elaborates the relationship between science and society. To scrutinize its connections to NoS approaches, we employed the Expanded FRA approach since it effectively addresses the complexity of the socio-institutional element of science which is underrepresented in most NoS views and, more generally, in traditional school science.

DEFINITIONS OF RESPONSIBLE RESEARCH AND INNOVATION (RRI)

The EU concept of RRI may be viewed as an adaptation of many contemporary ethical, educational and political ideas arising from the interplay between research, industry and the public. RRI has a lot in common with the EU's "Science in Society" action plan launched in 2001, as well as with concepts like 'Public Engagement in Science', 'Dialogue', and 'Citizen science', all of which form a wider agenda for democratising science and open it up to citizens' participation. Since 2010, the focus has been on developing a framework for RRI, which aims to align research and innovation with the values, needs and expectations of society. RRI is a key objective in the Horizon 2020 framework of the European Commission. It sets guidelines for responsibility in research and innovation, such as anticipation, reflexivity, inclusion and responsiveness (Stilgoe, Owen, & Macnaghten, 2013).

An early definition of RRI was provided by Sutcliffe (2011) in "A report on Responsible Research and Innovation", focusing on societal desirability, inclusive participation, ethical considerations, openness, anticipation and governance. The same elements constitute the later definition by von Schomberg (2013, p. 9): "*Responsible Research and Innovation is a transparent, interactive process by which societal actors and innovators become mutually responsive to each other with a view to the (ethical) acceptability, sustainability and societal desirability of the innovation process and its marketable products (in order to allow a proper embedding of scientific and technological advances in our society)*". As noted in a comprehensive review by Burguet, Bardone, and Pedaste (2017), this definition is closely connected to the European Union policies and has remained widely used and acknowledged in the literature.

The definitions of Sutcliffe (2011) and von Schomberg (2013) were formalized in the white paper titled "Responsible research and innovation – Europe's ability to respond to societal challenges" (European Commission, 2012) which presents RRI as an umbrella of explicit key points:

- the consistent, ongoing *engagement* of all societal actors – such as academia, industry, policy makers, non-governmental organizations and civil society – in the research and innovation process;
- *gender equality* to unlock the full potential of individuals regardless of their gender;
- *science education* to equip better future researchers and other societal actors with the necessary knowledge and tools to participate fully and take responsibility for the research and innovation process;
- promoting *open access*, transparency and accessibility to boost innovation and to increase the use of scientific results by all societal actors;
- *ethical issues*, i.e. the deliberate focus of research and innovation on achieving increased social or environmental relevance, acceptability and benefit; and
- *governance* models for integrating all RRI elements with adaptable and better oversight mechanisms to anticipate and manage problems and opportunities.

In addition, two more keys have been recently added to the umbrella of RRI in the Report from the Expert Group on Policy Indicators (European Commission, 2015b):

- *Social justice/inclusion*, aimed at avoiding the unfair exclusion of particular groups from either participation in research and/or access to benefits arising from research; and
- *Sustainability*, aimed at bridging the current knowledge gap about the capability of research programmes and RRI initiatives to contribute to sustainable growth according to H2020 strategy.

Another – and less normative – approach to RRI has an emphasis on shared values between the aforementioned societal actors. Reforms may not always be directly beneficial to everyone. For example, open access may not be in the immediate interests of industry or science publishers. Therefore, societal actors have to compromise and collaborate mutually to find the best solutions via democratic and socio-empirical bottom-up processes (Ruggiu, 2015).

For these purposes, science education is one of the more important keys to socially and ethically-sensitive inquiry. In its recent science education visions, the European Commission states: "A more responsive science education can promote broader participation in knowledge-based innovation that meets the highest ethical standards and helps ensure sustainable societies into the future" (European Commission, 2015, p. 7). Yet, despite the breadth of definitions and conceptualizations in the literature on RRI in general (Burguet et al., 2017), science education aspects of the concept are still poorly developed.

CONCEPTUAL RELATIONSHIP BETWEEN RRI AND NoS

In the recent white paper on European science education, the high-level expert group recommends that greater attention should be given to promoting Responsible Research and Innovation (RRI) and, in particular, "Science educators, at all levels, have a responsibility to embed social, economic and ethical principles into their teaching and learning in order to prepare students for active citizenship and employability" (European Commission, 2015). In their analysis of the meanings of RRI in science education, Heras and Ruiz-Mallén (2017) state that RRI-style science education should contribute to students' engagement with science and empower them as responsible citizens, which requires critical thinking skills, reflexivity about science, and embedding of social and ethical processes. We argue that the socio-institutional aspects of NoS, as described in the previous section, provide a natural context for such discussion and a plausible way for operationalizing RRI in classrooms.

It is evident that Erduran and Dagher's (2014) approach to NoS considers science not only as a body of knowledge but also as a complex process, involving not only facts but also multiple perspectives, interests, uncertainties and values. Thereby, the modern conception of NoS aligns with RRI in shifting the perception of science from being neutral, discipline-bound and isolated, to being inherently value-laden, transdisciplinary and responsive to socio-scientific issues. RRI addresses science as a socio-institutional system – not that much the cognitive-epistemic side. Thereby we focus on the elements of the Nature of Science presented in **Figure 1**.

Here we examine the eight normative key points of RRI, and how they are connected to the seven features of science as a social-institutional system. The connections are depicted in **Figure 2**, and discussed in detail in what follows.

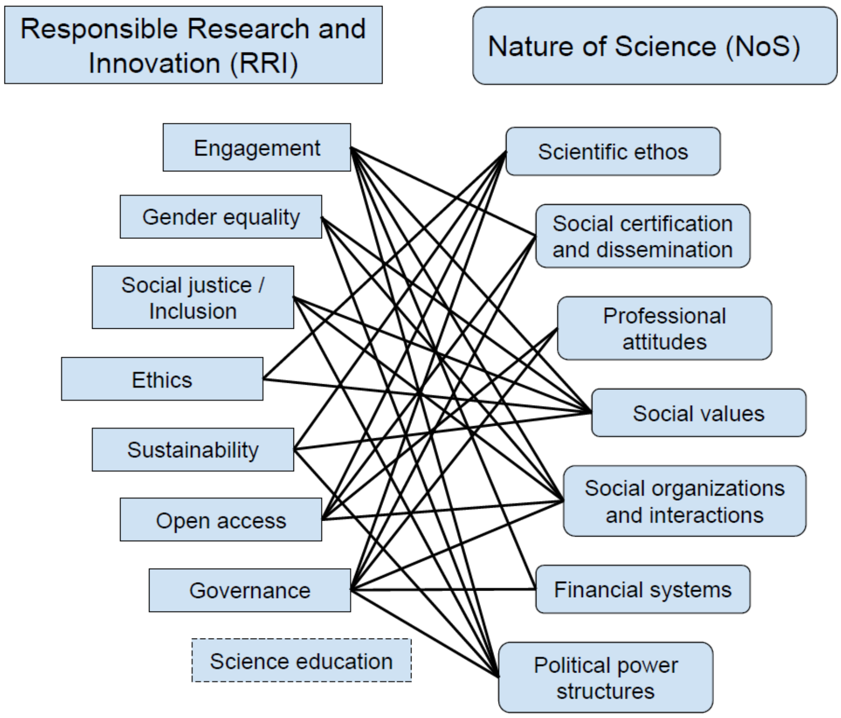

Figure 2. The connections between the dimensions of Responsible Research and Innovation (RRI) and the socio-institutional dimensions of the Nature of Science (NoS) in the Expanded Family Resemblance Approach.

RRI 1: Engagement

With the first RRI element, the European Commission calls for the consistent, ongoing involvement of society (the public, NGOs, industry, policy-makers and other stakeholders) from the beginning to the end of the research/innovation process, and for assessing and prioritizing social, ethical and environmental impacts, risks and opportunities, alongside the technical and commercial (Sutcliffe, 2011). Joint participation, mutual learning and agreed practices of all societal actors in the research and innovation process reflect the value of inclusiveness and are supposed to lead to greater societal acceptability of innovations and their benefits to society.

In science communication terms, this RRI principle calls for an 'upstream engagement' of the public. Societal challenges addressed in inquiry and innovation should be framed on the basis of widely-representative social, economic and ethical concerns and common principles. Having the involvement of the public and non-governmental groups, who themselves are mindful of the public benefit, is the key here.

In our view, these issues connect with five of the NoS features included in the Expanded Family Resemblance Approach:

- Social Values of Science
- Social Organisations and Interactions
- Political Power Structures
- Financial Systems

For example, the theme of Social Organisations and Interactions deals with "understanding how scientists work within and across social organizations and how they interact with each other as well as with stakeholders" (Erduran & Dagher, 2014), which is central in the RRI idea of engagement. The same goes for the interplay between science and politics (Political Power Structures) and that science has an economic dimension (Financial Systems). The engagement of different societal actors can be discussed in the context of these NoS features which have considerable overlap with the first RRI dimension.

RRI 2: Gender Equality

With the second RRI dimension, the European Commission (2012) mostly refers to the need to address the under-representation of women in science and technology, such as by modernizing the research institutions, in particular their human resources management. Indeed, several studies have shown that women do not have equal numbers nor opportunities in these fields and this inequality has been difficult to solve due to structural and subconscious factors. But this dimension goes beyond this challenge, too: "The gender dimension must be integrated in research and innovation content" (European Commission, 2012). This represents a step to address the notion that the direction of scientific research is affected by informal influences within the culture of science itself.

Thereby, the Gender equality dimension of RRI can be addressed in the context of the following NoS elements:

- Social Values of Science
- Social Organisations and Interactions
- Political Power Structures

Political Power Structures are suggested as being a part of NoS, and by that concept Erduran and Dagher (2014) mean, besides other things, to unveil how science or any other human endeavour is not neutral in gender, and how science and science education can alienate girls and women. The RRI aim of enhancing gender equality and thereby "unlocking the full potential of society" (European Commission, 2012; see also Sutcliffe, 2011) can be promoted by discussing social values, organisations and interactions in NoS teaching.

RRI 2b: Social Justice / Inclusion

The Social Justice / Inclusion element was added to RRI by an Expert Group on Policy Indicators (European Commission, 2015b) to avoid the exclusion of particular groups from participation in research and/or accessing benefits arising from research.

Accordingly, in NoS, social utility and freedom are considered to be social values that are embodied by science. Furthermore, according to the model, science education should address political power structures that can endanger social justice and social inclusion. In particular, science education has the responsibility to "unveil how scientific knowledge can become a tool for oppression and exploitation to countless victims when co-opted to serve gender, colonial, economic or other interests, and in the process, alienate individuals or groups like women, de-humanize communities, destroy ecologies and cultures" (Erduran & Dagher, 2014).

The RRI dimension of Social Justice / Inclusion touches and extends the Gender equality dimension. These themes are addressed in depth in the following NoS features:

- Social Values of Science
- Social Organisations and Interactions
- Political Power Structures

RRI 3: Science Education

According to the RRI framework, science education plays a major role "[…] to better equip future researchers and other societal actors with the necessary knowledge and tools to fully participate and take responsibility in the research and innovation process" (European Commission, 2012). The Commission emphasizes the urgent need to boost the interest of children and youth in mathematics, science and technology for two purposes: to attract and educate future researchers, and to contribute to a scientifically literate society. Creative thinking skills are considered important in building the future with science and innovation (European Commission, 2012).

This RRI aspect overlaps significantly with the general aims of NoS teaching. The very same arguments for better science education have been made to justify NoS teaching. Yet, NoS has been conceptualised in science classrooms in a much more profound way. Furthermore, NoS teaching has been proven to increase the student interest and motivation (Roberts, 2007) called for by the EU (European Commission, 2012).

Yet, this RRI aspect ("Science education") is not specific to individual NoS elements in the same way as the others are. This RRI aspect, above all, simply points out that science education is crucial in pursuing RRI in society in general. This general claim is certainly easy to agree with in the science education community, and all NoS elements can be considered to work to that end. Therefore, we consider the link of this RRI aspect to NoS to be different from other RRI aspects. It is more intimate, and it falls beyond the analysis of this level.

RRI 4: Ethics

With the RRI dimension labelled 'Ethics', the EC necessitates respecting fundamental rights and the highest ethical standards in all research and innovation. This involves not only legal aspects but also the deliberate focus of research and innovation to achieve increased social or environmental relevance, acceptability and benefit. Thereby, the Ethics dimension of RRI emphasizes responsibility towards society and all its actors, and it "should not be perceived as a constraint to research and innovation, but rather as a way of ensuring high quality results" (European Commission, 2012).

This is clearly linked to scientific ethos as a feature in NoS. That element refers to "attitudes that scientists are expected to adopt and display in their interactions with their fellow scientists as well as in carrying out their scientific activities" (Irzik & Nola, 2014, pp. 1006–1007). When students are taught about scientific ethos (to deliver an image of the ethical practices of scientists), this RRI aspect can be addressed in a natural way. Also, in NoS, respecting the environment and social utility are considered to be social values that are embodied by science. Furthermore, in their model, Erduran and Dagher (2014) highlight that science has a financial dimension. Research funding institutions play a role in determining the goals of research, and most public research funders stress social and ethical acceptability and benefit.

Thereby, ethical issues highlighted by the RRI framework are deeply embedded in NoS, especially in the following dimensions:

- Scientific Ethos
- Social Values of Science
- Financial Systems

RRI 4b: Sustainability

Sustainability is another element added to the concept by the Expert Group on Policy Indicators (European Commission, 2015b), recognizing that this key was not addressed sufficiently or explicitly enough in the six original dimensions. Yet, it is intimately linked to the Ethics dimension. Sustainability in RRI refers to fostering the capability of research programmes and RRI initiatives to contribute to sustainable growth according to the H2020 strategy. It stresses researchers' responsibility for the safety and the quality of the environment.

As the 'Ethics' dimension, the sustainability dimension deals with Scientific Ethos in NoS (Erduran & Dagher, 2014). Furthermore, respecting the environment and its sustainability are considered Social Values that are embodied by science.

- Scientific Ethos
- Social Values of Science

RRI 5: Open Access

The European Commission (2012) argues that in order to be responsible, research and innovation must be transparent and accessible. The EC has strongly and effectively pushed academia to provide free access to the results of publicly-funded research, including not only publications but data as well. Also, this aim is both value-based and instrumental: openness is expected to boost innovation and increase the use of scientific results by all societal actors.

The aim of open access is certainly a key issue in Professional Activities but also several other aspects of NoS:

- Social Certification and Dissemination
- Professional Activities
- Scientific Ethos
- Social Organisations and Interactions

Discussing the RRI aspect of open access, and utilising some of the real data or scientific publications in science education, may raise students' awareness of the ways to act, think and communicate in science.

RRI 6: Governance

The last RRI component mostly concerns policy-makers. The Governance dimension of RRI highlights policy-makers' responsibility to prevent harmful or unethical developments in research and innovation. The policy makers should develop better and adaptable oversight mechanisms with all stakeholders, to anticipate and manage problems and opportunities. This requires governance models for integrating all RRI elements (European Commission, 2012; Sutcliffe, 2011).

This RRI element does have implications for science education too. Since it implies that scientists have to disseminate and interact with policy-makers and discuss ethical issues with them and help them create oversight mechanisms, such issues are a part of NoS as a socio-institutional system.

In this sense, almost all of the NoS features have this aspect of governance.

- Social Certification and Dissemination
- Professional Activities
- Scientific Ethos
- Social Organisations and Interactions
- Political Power Structures
- Financial Systems

Put together, this comparison showed many mutual connections between the concepts of RRI and the socio-institutional dimensions of NoS in the Expanded Family Resemblance Approach. The latter offers a comprehensive platform to address all RRI aspects in science education. We will discuss these opportunities further after first presenting examples from an EU project.

RRI IN NoS TEACHING: EXAMPLES AND EXPERIENCES

In this section we present examples and experiences from IRRESISTIBLE, EU project funded from 2013 to 2016, to illustrate how RRI may be implemented in NoS teaching and to explore teachers' responses to those approaches.

The goal of the IRRESISTIBLE project was to design activities that foster the involvement of students and the public in the process of RRI (Apotheker et al., 2017). To address the goals of RRI, the project was aimed at increasing students' knowledge about contemporary research and its nature. This was achieved by combining formal and informal educational approaches to discuss RRI issues in the context of relevant topics and cutting-edge research.

Pedagogical Approaches for RRI and NoS Teaching

In each of the ten partner countries in the IRRESISTIBLE project, communities of learners developed thematic modules. These groups were comprised of school teachers, educational experts from universities, exhibition experts from museums and science centres and researchers from the respective thematic fields (Apotheker et al., 2017). There was no given standard procedure for module development within the project; moreover, the different communities of learners drew on existing material or prior experience and expertise, and followed the most promising approach respectively. Most groups developed their modules by attending to the scientific topic and its relevant socio-scientific issues. Subsequently, the RRI aspects were highlighted in the material, and augmented if necessary before the material was fully developed. Some of the communities, like the group from Portugal, worked the other way round: they started with the six RRI dimensions and subsequently wove the content into that frame. Although NoS teaching was not the explicit objective for the modules, the developers found many well-known NoS teaching approaches very apposite for addressing the RRI dimensions.

This way, 17 teaching modules were developed, covering various contemporary research topics like nanoscience, climate research, innovative materials for solar cells, geoengineering, and ocean research. (Modules available at http://www.irresistible-project.eu/index.php/en/resources/teaching-modules). All modules were tested by the teachers developing them and subsequently exchanged with other partner countries for another implementation.

The IRRESISTIBLE project built on the six aspects approach to characterize RRI as proposed by Sutcliffe (2011) and verbalized in a catchy way by the European Commission (2012). The two additional RRI aspects, Social Justice / Inclusion and Sustainability, were not explicitly integrated into the IRRESISTIBLE modules since they were added to the RRI framework after the module development took place (European Commission, 2015b). Those themes were, however, implicitly addressed within the dimensions Gender Equality and Ethics.

During the module development, two major challenges emerged. The first was to understand fully the concept of RRI and to adapt it meaningfully to the school level. The concept itself was written from a research perspective, i.e. looking at the aspects with a full understanding of how science works. This created some challenges, particularly for the teachers working in the communities of learners. A special workshop was organized to address this issue (Blonder et al., 2017) and to exchange ideas to form a shared understanding of RRI within the project. Another challenge was to find the pedagogical methods for RRI in science classes. In particular, the question of whether RRI should be taught explicitly or implicitly was hotly debated (cf. de Vocht et al., 2017). Explicit teaching may create a higher visibility of RRI for students, but with the risk of appearing as though it has been artificially set on top of the topic. Implicit teaching provides a close connection and natural integration to the subject, but with the danger of losing sight of RRI in the great diversity of the cutting-edge research topics. Several approaches were discussed, such as scenario-based learning, role-play or student-curated exhibits (Kampschulte & Parchmann, 2015), using both implicit and explicit approaches. In the communities of learners, very different environments, where students take active parts, discuss, judge, argue, value, and learn RRI while learning scientific phenomena, were created. For example, in the Turkish module discussing bacteria resistant to antibiotics, RRI was more or less integrated in the whole module. In the Dutch module discussing the difference between cow milk and mothers milk, RRI was introduced explicitly in the exploration phase. The RRI dimensions were introduced and linked to different aspects of the scientific knowledge in the module (Apotheker et al., 2017). Both approaches worked for the teachers.

Most typically, the integration of RRI was realized in the module activities addressing one RRI aspect specifically. For example, the most popular approach to integrate the dimension of Engagement was to use a role play: Making students take the roles of different societal actors and debate for example, the issues of nanoscience in order to learn about its complex societal connections. Such methods have been used successfully in NoS teaching when addressing aspects like Social Organizations and Interactions, Political Power Structures, and Financial Systems (Erduran & Dagher, 2014).

Table 1 lists an example from the IRRESISTIBLE teaching modules for each RRI aspect, and adds the related NoS aspects in the last column. The table demonstrates how the instructional methods employed in IRRESISTIBLE to teach RRI closely resemble the approaches for teaching the socio-institutional dimensions of NoS (sections 2 and 4).

Table 1. Examples of integrating Responsible Research and Innovation (RRI) aspects in the teaching modules and their Nature of Science (NoS) equivalents.

RRI Aspect	Example from the teaching modules	NOS Aspects
Engagement	Students took the roles of stakeholders who deal with these issues as part of their everyday life. Roles were taken for a single discussion or through the whole module.	• Social Organizations and Interactions • Political Power Structures • Financial Systems
Gender Equality	Analysis of documentary videos or scientific articles to reflect gender distribution in research and subsequently discuss these issues.	• Political Power Structures • Social Organizations and Interactions
Science Education	Students train their practical scientific skills: designing and performing experiments, collecting and analysing data, interpreting and discussing findings.	• All NoS teaching and learning, both cognitive-epistemic and socio-institutional aspects
Open Access	To weigh up prospects and risks of a topic, students searched and used scientific articles. When hitting the pay wall for closed access publications, the topic of open access (in a broader sense) was discussed.	• Social Certification and Dissemination • Professional Attitudes
Ethics	Discussion on ethical standards, criteria, and the dilemmas associated with open-ended research. SWOT analysis to structure and sum up the results of the debate on benefits and limitations of novel technologies.	• Scientific Ethos • Social Values of Science • Financial Systems
Governance	Group work or group discussion based on a statement of a political group or a part of a regulatory act.	• Social Certification and Dissemination • Social Organizations and Interactions • Political Power Structures • Financial Systems

Although the most common approach was to develop activities focusing on one of the six RRI dimensions, some of the countries integrated all RRI aspects into a single activity: In two of the modules, the RRI dimensions were worked out in three consecutive lessons and then presented as one area in the final student-curated exhibition. In another module, a dice game served as tool for developing the RRI aspects. Students played with two dice: One die was labelled with the six RRI aspects on the sides, the other die had six scientific module-related terms. When throwing the dice, students always got a combination of an RRI aspect and a scientific term. Their task in the group was then to come up with an example where the aspects are connected. The game not only served as a tool to recapitulate and discuss the RRI dimensions, but also to find relevance for these aspects in (nanotechnology) research and everyday life. In addition, the game trained students in various other skills like communication, willingness to compromise, and teamwork.

The wide variety of activities to integrate the different RRI aspects in the teaching modules shows not only the creativity of the communities of learners, but also the educational adaptability of the RRI concept. As presented with the examples above (**Table 1**), integrating RRI through NoS teaching approaches seems feasible.

Teachers' Attitudes about RRI Teaching

Since teachers play a make-or-break role in any curriculum innovation, we briefly discuss our findings on teachers' interests and concerns when adopting RRI in their teaching. Sixty-seven science teachers from all school levels and 10 European countries were surveyed during the first round of IRRESISTIBLE (de Vocht et al., 2017), and 180 teachers during the second round (de Vocht & Laherto, 2017). These surveys employed the Stages of Concern questionnaire (Hall, George & Rutherford, 1977; Liu & Huang, 2005) which was adopted in the first round and further developed in the second round (for full details of the instruments and analyses, see de Vocht & Laherto, 2017; de Vocht et al., 2017). The results showed that during the first round, teachers were mainly interested in finding information on RRI and learning about it. Teachers were also interested in collaborating with other teachers when adopting RRI. However, teachers voiced some concerns related to their personal ability to teach RRI and management of resources within already busy teaching schedules. These concerns were not resolved during the project, as the pre/post-survey comparison showed (de Vocht et al., 2017).

The larger sample in the second round allowed for a more thorough analysis using cluster analysis (de Vocht & Laherto, 2017). As in the first round, concerns and interests were first divided into different themes – or "stages of concern" (cf. Liu & Huang, 2005) – such as information, management and collaboration. The questionnaire items dealt with several types of concerns and interests, e.g. item "*I am not competent in teaching RRI*" addressed a more serious and intrinsic concern than item "*I am concerned about not having enough opportunities to develop my RRI teaching*". The improved questionnaire also took into account the distinction between negative concerns (worries) and positive concerns (interests). The analysis employed multiple clustering methods. Both k-means cluster analysis and hierarchical cluster analysis with Ward's method resulted in four distinct clusters for the negative concern items, and three clusters for positive concerns, i.e. interests. Profile types were identified using the concern clusters, whereas the interest clusters acted as a subcategories; for full information on the methods and results of the cluster analysis, see de Vocht and Laherto (2017). The major profile types were the "Carefree", the "Pragmatic" and the "Uncertain". The "Carefree" profile type had few concerns and a great deal of interest in adopting RRI in their teaching: they felt confident about their personal knowledge and skills in RRI, ability to manage RRI teaching in practice, and to improve their practices, to collaborate with other teachers, and to influence students in a positive way. The "Pragmatic" group was similar to the "Carefree", but had significantly more concerns related to finding information about RRI and allocating teaching resources to it. Finally, the "Uncertain" group had major concerns related to their ability to teach RRI (de Vocht & Laherto, 2017).

The high number of "Uncertain" teachers calls for better conceptualization of RRI in the school context. Furthermore, when interpreting these results, one must keep in mind that the teachers in the IRRESISTIBLE project were forerunners and may not represent the average teacher. It is safe to say that if RRI is to be disseminated on a wider scale across Europe, more concerns are to be expected from teachers. Teaching innovations which originate from outside school typically face more opposition than innovations created by teachers and educators (de Vocht et al., 2017). Therefore, discussing RRI in the context of NoS, with which teachers are already more familiar, may facilitate the incorporation of RRI elements in science education.

In Turkey, a *Nano and Health* module was implemented by twenty-four science teachers (of biology, chemistry, physics) at 19 schools as an extra-curricular activity for about 12 weeks. After completing the module, teachers were given a questionnaire including 16 open-ended questions asking to evaluate module implementation in terms of student gains of content knowledge and skills. Specifically, one of the questions in the questionnaire was; "*Please indicate three RRI-related objectives you think that your students attained by completing the Nano and Health module.*"

For this question, a total of 59 responses were obtained from the teachers. These responses were coded through inductive content analysis, and analysed according to the meaningful categories emerged. About 20% percent of the responses were coded by another researcher, and then discussed until reaching full interrater agreement. According to the teachers, the module helped their students raise awareness about RRI (41%), learn about RRI (39%), take action for RRI (10%), integrate RRI into nanotechnology (7%), and develop beliefs about RRI. The analysis and results were described in detail elsewhere (Akaygun & Adadan, 2017), and here just briefly discussed in context of RRI and NoS teaching.

The category "learn about RRI" can be associated with the cognitive-epistemic element of NoS (Irzik & Nola, 2014), dealing with understanding concepts, models, laws and theories. Teachers suggested that the greatest number of students (41%) gained an "awareness" of RRI. This category matches well with the Scientific Ethos and Social Values components of science as a social institution, since teachers indicated that students started to value ethics, honesty, openness, critical attitude, gender equality, and universalism. Few teachers (10%) argued that their students learnt to "take action" regarding RRI. This gain can also be associated with the Social Values components of Science as a Social institution: as the students develop values like autonomy and social utility, they could start engaging in societal issues and taking action for RRI. Furthermore, very few teachers (7%) indicated that students learned "integrating RRI to the context", which can be linked to learning the socio-institutional dimensions of NoS (Erduran & Dagher, 2014). In other words, very few teachers thought that their students could see RRI in a broader perspective, consider the role of larger systems wherein RRI is embedded and effectively functions as a part of the system. Finally, very few teachers (4%) indicated that their students developed "beliefs about RRI", which can also be associated with the Scientific Ethos component because students develop critical attitudes, universalism, and respect for RRI. The reason for having only a small percentage of teachers acknowledging students' gains regarding "action", "integration of RRI" and "beliefs" could indicate that these gains are higher order because they require more effort and experience. The gains regarding "knowledge" and "awareness" could be considered to be lower order as they were fundamental, relatively easier, and hence achieved by the majority. This small analysis (for further details, see Akaygun & Adadan, 2017) showed that there seems to be a connection between students' gains in RRI and NoS due to the similarities in their nature.

One of the more debated questions during the IRRESISTIBLE project was whether RRI should be taught implicitly or explicitly. This item divided teachers roughly in half during both rounds of project (de Vocht & Laherto, 2017; de Vocht et al., 2017). This issue, similar to the one discussed in the previous section concerning the approaches adopted in the modules, is further discussed in the concluding section.

Furthermore, an additional instrument to analyse teachers' attitudes about RRI was developed and administered to teachers participating in the IRRESISTIBLE project (Blonder et al., 2017). The questionnaire, including two items for each RRI dimension, enabled the researchers to examine the changes in the teachers' attitudes about RRI. The process of teacher professional development in the project, that included a direct explicit teaching of the RRI dimensions, led to a positive, statistically significant change in teachers' attitudes to RRI as a general construct and for four of its dimensions separately (results for the dimensions of engagement and gender equality were not statistically significant).

The questionnaire included another part in which the teachers were asked to rate the responsibility for RRI of different stakeholders (scientists, educators, environmental organizations, NGOs, consumers, businesses, the printed and electronic media, the government, and academic institutions) in the real world and in an ideal world (for further details of the questionnaire, see Blonder et al., 2017). An interesting aspect detected from this part of the questionnaire was teachers' perspectives regarding their own role in promoting RRI. When the teachers were asked "In an ideal world, what degree of responsibility should each specific group take for RRI (for the consequences of research and innovation in society and the environment)?" they gave it a very low grade (less than 2, in a scale of 1-5) for educators. This grade remained low even after the teachers participated in the IRRESISTIBLE project (Blonder et al., 2017). This result shows that although the teachers developed positive attitudes about the RRI construct they still do not quite recognize their role and their responsibility as science teachers to promote RRI. The finding highlights the need to contextualize RRI better in current practices of science education, which was the aim of the present paper.

CONCLUSIONS

Both the concept of RRI (European Commission, 2012) and the recent recommendations for school science (European Commission, 2015) push European science education towards addressing science as a socio-institutional system. It is likely that the concept of responsibility, with its dimensions specified by the concept RRI, will be at the core of European science education in the next decades. This trend will arguably highlight and contribute to the modern conceptions of Nature of Science (NoS) in science classrooms.

While RRI has so far mostly remained a concern of academia, the concept is gradually entering school education also. For example, in some European systems, school teachers can acquire additional credit for adopting RRI and embedding it in their practice (Kearney, 2016). This is a worthwhile strategy, since teachers play a key role in the diffusion of RRI in schools (de Vocht et al., 2017). Our experiences, however, show that contextualising RRI in science classrooms is not an easy task. We assume that connecting the concept of RRI into existing approaches and trends – such as NoS teaching – would help teachers, curriculum developers and educationists in incorporating RRI in the curriculum and in finding suitable pedagogical approaches for it.

The conceptual analysis carried out in this paper is comparable to that undertaken by Blonder et al. (2016) about the connections of RRI to another central framework of science education, the Socio-Scientific Issues (SSIs). They pointed out that SSIs fit well together with the RRI obligations of the scientists to contribute to the field of science education and public engagement. Blonder et al. (2016) concluded that most of the RRI dimensions are at least mentioned in the SSI literature, although not in a systematic way. In the present paper we highlighted connections between RRI and NoS that are at least as strong, and argue that relatively well-established NoS teaching also provides an excellent platform to incorporate RRI in classrooms. Our concept analysis and practical examples show that the socio-institutional NoS activities, developed by the science education community, align especially well with the RRI aims, i.e. promoting a culture of responsibility, participative inquiry and debate among different stakeholders. This overlap makes it possible to employ the recommendations and practical applications of the Expanded Family Resemblance Approach (Erduran & Dagher, 2014) to address RRI in classrooms.

Yet, further research is needed to fully operationalize RRI in science education and to find assessment criteria for it. Which values of science should be addressed in science education, and how? What kind of learning objectives should be set for RRI (cf. Heras & Ruiz-Mallén, 2017)? Within the IRRESISTIBLE project, formulating learning goals was found to be difficult. RRI entails a specific emphasis on deep engagement between the public and different societal actors in the processes of research and innovation, aiming at promoting the responsiveness, ethical acceptability, sustainability and societal desirability of these processes. These societal concerns bring a new layer to current NoS approaches. For evaluating RRI learning, well-established NoS questionnaires are a good start, but not enough.

In the approaches developed for RRI teaching in the IRRESISTIBLE project, another recurrent question was if the RRI dimensions should be explicit or implicit in teaching and learning (Apotheker et al., 2017; de Vocht et al., 2017). This debate resembles the dispute on whether NoS should be taught explicitly or implicitly (Lederman, 2007). However, RRI is a far less neutral and more formative and value-laden concept than NoS. RRI teaching, thereby, has to address a further question: should teachers teach RRI as a normative set of values, or should they support students in their own meaning-making and to come up with their own set of values considering the societal aspects of research and innovation? In some IRRESISTIBLE teaching modules, RRI was foregrounded, in some modules backgrounded. Some communities of learners chose to teach RRI explicitly as a normative set of key points, for example making students study the EU documents and prepare presentations about each RRI key-point as such. Some communities of learners combined RRI with a context in an implicit way, implying that students should be encouraged to discuss and come up with a diversity of viewpoints and reasoning regarding the values and aims of the society.

Such classroom discourse could lead RRI teaching towards the socio-empirical version of RRI (Ruggiu, 2015). One way to apply this in teaching, as solved in several IRRESISTIBLE modules, is to present students with an RRI-related conflict of interest, and let students assume different societal roles. In this way, students can create a dynamic view of how the RRI-related values of our society can be formed. Such a socio-empirical way to teach RRI is not possible if RRI is presented explicitly to the students as a set of key points. Teachers, however, can use the key points as a loose guide when planning their lessons, while not presenting them directly in the teaching-learning content.

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